Implications of the dimuon asymmetry in $B_{d,s}$ decay

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Outline

- Briefly: theory same sign lepton CP violation (CPV).

- General interpretation + linkage (?) with CPV in $B_{s,d}$ mixing

=> model indep' interpretation.

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=> model indep' interpretation.

- Minimalism: MFV explanation & GMFV (general minimal flavor violation).

- New realization: ultra-natural warped model & flavor triviality.

- Summary.

Same sign leptons CP asymmetry, formalism

- Effective H for $B_q, \bar{B}_q$: $\mathcal{H} = M + i\Gamma/2\,;$
  Mass eigenstates: $|B_{L,H}\rangle = p|B_q\rangle + q|\bar{B}_q\rangle\,.$

=> $$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}$$

Hence: $$a_{\rm SL} = \frac{1-|q/p|^4}{1+|q/p|^4} \qquad \left(a_{\rm SL}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \right)$$

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$$M_{12} = |M_{12}|e^{i\phi_M} \quad , \quad \Gamma_{12} = |\Gamma_{12}|e^{i\phi_\Gamma}\ .$$

=> $$a_{\mathrm{SL}} = -\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin(\phi_M - \phi_\Gamma).$$

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- SM (GIM): $a_{\rm SL}^{d,s} \sim \frac{m_c^2}{m_W^2} {\rm Im}\left(\frac{V_{cb}V_{cd,s}^*}{V_{tb}V_{td,s}^*}\right) = \mathcal{O}\left(10^{-2,-4}\right)$

Dø reports 3.2σ in dimuon asymmetry; CDF improves $\Delta\Gamma_s$ vs. $S_{\psi\phi}$??

- **D0 result:** $$a^b_{\rm SL} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3},$$

1005.2757.

fragmentation correlates $B_d \leftrightarrow B_s$

$$a^b_{\rm SL} = (0.506 \pm 0.043)\, a^d_{\rm SL} + (0.494 \pm 0.043)\, a^s_{\rm SL}\,.$$

Grossman, Nir & Raz, PRL (06).

- Data favors NP in B_s : $\left(a^d_{\rm SL}\right)_{\rm exp} \ll a^b_{\rm SL} \Rightarrow a^s_{\rm SL} \sim a^b_{\rm SL}$

- Requires large new phase, $a^s_{\rm SL} = -\left|\frac{\Gamma_{12}}{M_{12}}\right|_s \sin(\phi_M - \phi_\Gamma).$

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- Origin of phase? $\Delta\Gamma_s^{\rm NP} \Leftrightarrow$ overcome SM tree level and not violate other CPV, ex.: $b \to s\tau^+\tau^-$.

Dighe, Kundu & Nandi [0705.4547, 1005.4051]
Bauer & Dunn [1006.1629]

- Assuming no direct CP ↔ NP contributes to SM suppressed amplitudes => correlation \w other observables:

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$$a_{\rm SL}^s = -\frac{|\Delta\Gamma_s|}{\Delta m_s} S_{\psi\phi} \Big/ \sqrt{1 - S_{\psi\phi}^2}\,,$$

Ligeti, Papucci & GP, PRL (06);
Grossman, Nir & GP, PRL (09).

Correlation with $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

(more exciting results just after this talk)

- D0 result can be written as:

$$-|\Delta\Gamma_s| \simeq \Delta m_s \big(2.0\, a_{\rm SL}^b - 1.0\, a_{\rm SL}^d\big)\, \sqrt{1 - S_{\psi\phi}^2}\, /\, S_{\psi\phi}\,.$$

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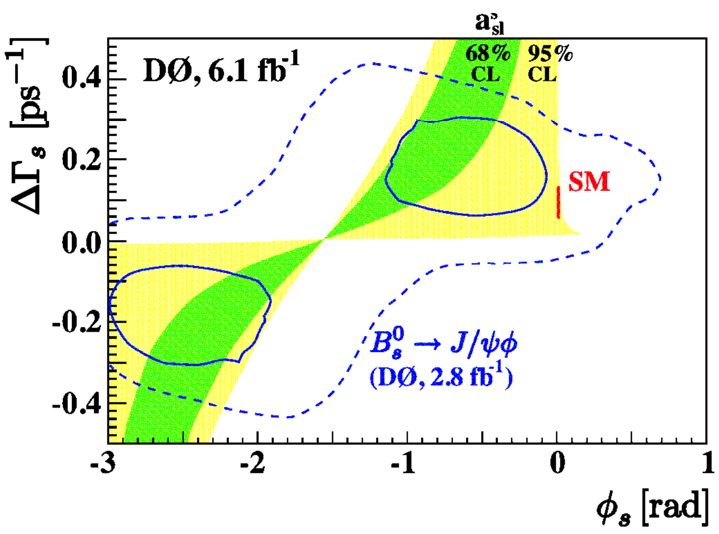
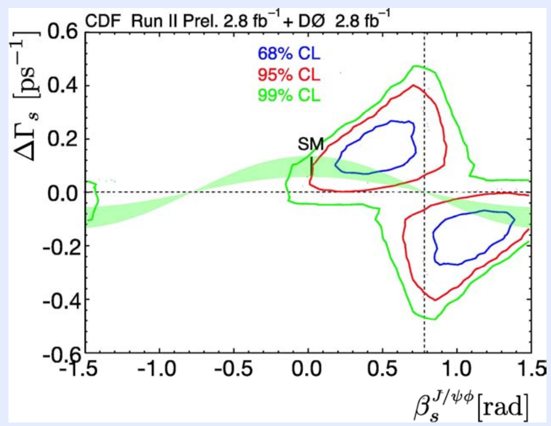
- Tevatron experiments also measure:

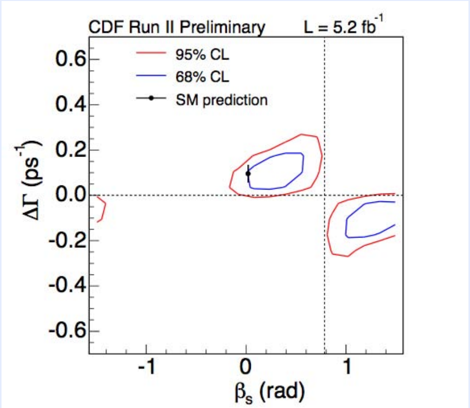




Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 σ)

CDF Public Note 9787

New CDF measurement of β_s



Coverage adjusted 2D likelihood contours for β_s and $\Delta\Gamma$

P-value for SM point: 44% (0.8σ deviation)

Correlation with $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

(more exciting results just after this talk)

- D0 result can be written as:

$$-|\Delta\Gamma_s| \simeq \Delta m_s \left(2.0\, a^b_{\rm SL} - 1.0\, a^d_{\rm SL}\right) \sqrt{1 - S^2_{\psi\phi}}\, /\, S_{\psi\phi}\,.$$

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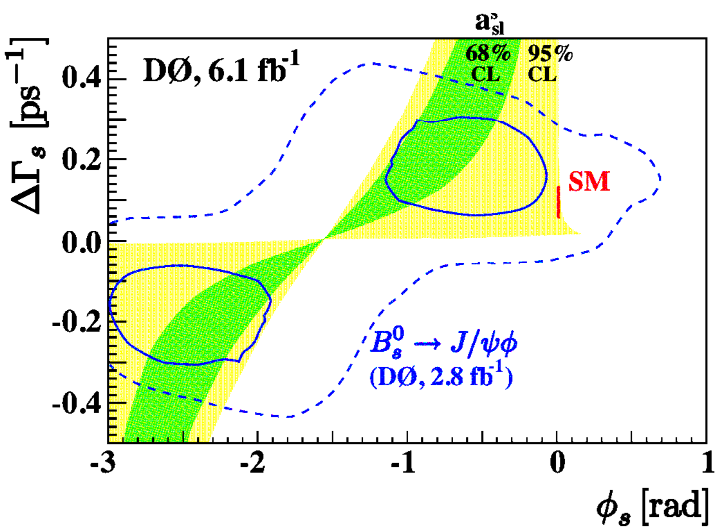

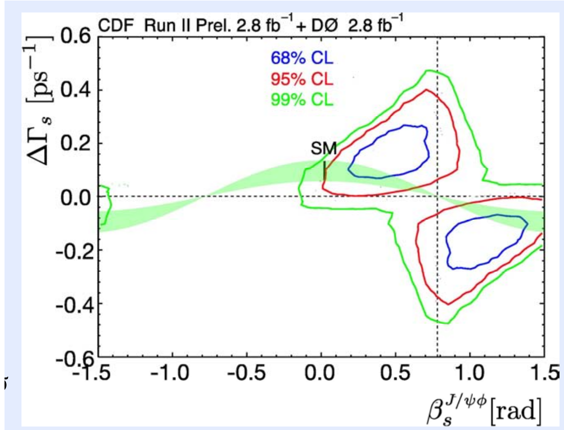

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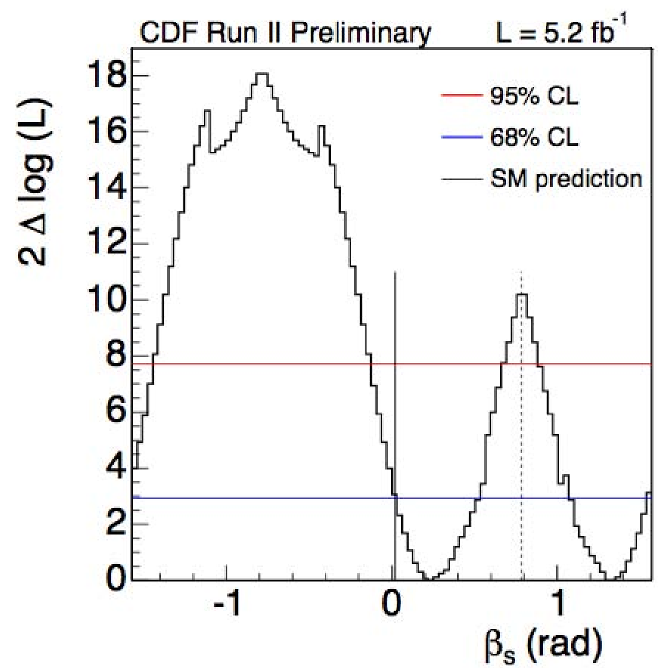


Combining a^b_{SL} & $\Delta\Gamma_s$ vs. $S_{\psi\phi}$

- Consistency check:

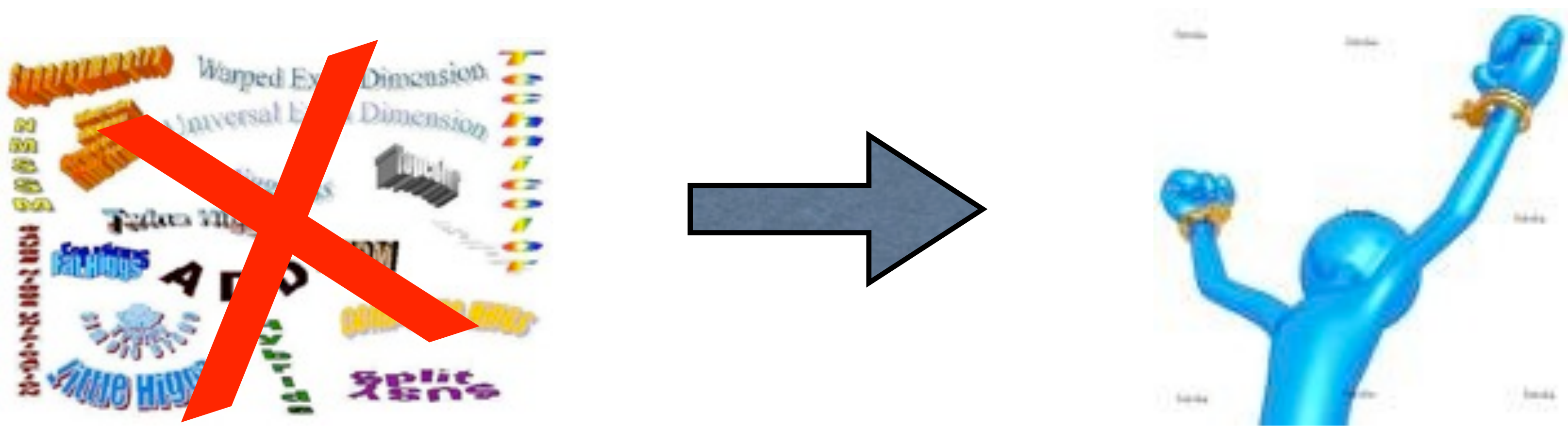
Ligeti, Papucci, GP, Zupan.

$$\left(a^b_{\mathrm{SL}}\right)_{\mathrm{D}\varnothing}: \qquad |\Delta\Gamma_s| \sim (0.28 \pm 0.15)\ \sqrt{1-S_{\psi\phi}}/S_{\psi\phi}\ \mathrm{ps}^{-1}$$

$$\left(S_{\psi\phi}\right)_{\mathrm{CDF+D}\varnothing}: \quad (\Delta\Gamma_s,\, S_{\psi\phi}) \sim (0.15\,\mathrm{ps}^{-1},\ \ 0.5)$$

- Can use data to fit $\Delta\Gamma_s$ => no theory involved.

Model independent interpretation



Global NP fit

Ligeti, Papucci, GP, Zupan.

- **Clean NP interpretation:** $M_{12}^{d,s} = \left(M_{12}^{d,s}\right)^{\rm SM} \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right).$

$(\Delta\Gamma_s$ is taken from the fit $\to$ not theory involved$)$

h_i : magnitude of NP normalized to SM.

σ_i : NP relative phase.

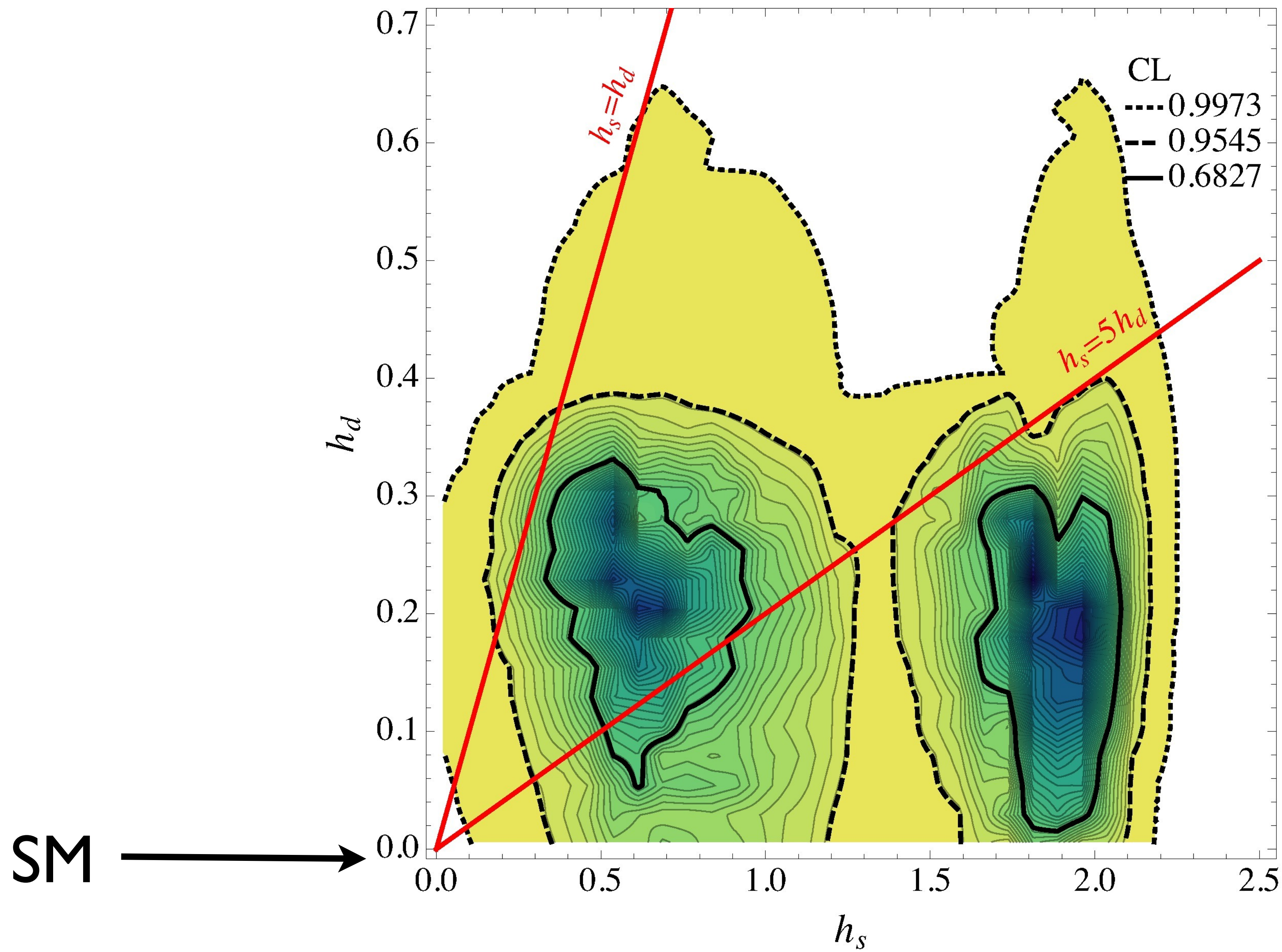
$$
\begin{aligned}
\Delta m_q &= \Delta m_q^{\rm SM} \left|1 + h_q e^{2i\sigma_q}\right|, \\
\Delta\Gamma_s &= \Delta\Gamma_s^{\rm SM} \cos\left[\arg\left(1 + h_s e^{2i\sigma_s}\right)\right], \\
A_{\rm SL}^q &= {\rm Im}\left\{\Gamma_{12}^q / \left[M_{12}^{q,{\rm SM}} (1 + h_q e^{2i\sigma_q})\right]\right\}, \\
S_{\psi K} &= \sin\left[2\beta + \arg\left(1 + h_d e^{2i\sigma_d}\right)\right], \\
S_{\psi\phi} &= \sin\left[2\beta_s - \arg\left(1 + h_s e^{2i\sigma_s}\right)\right].
\end{aligned}
$$

Global fit's results

Ligeti, Papucci, GP, Zupan.

(we used CKMfitter)

B_d vs. B_d systems



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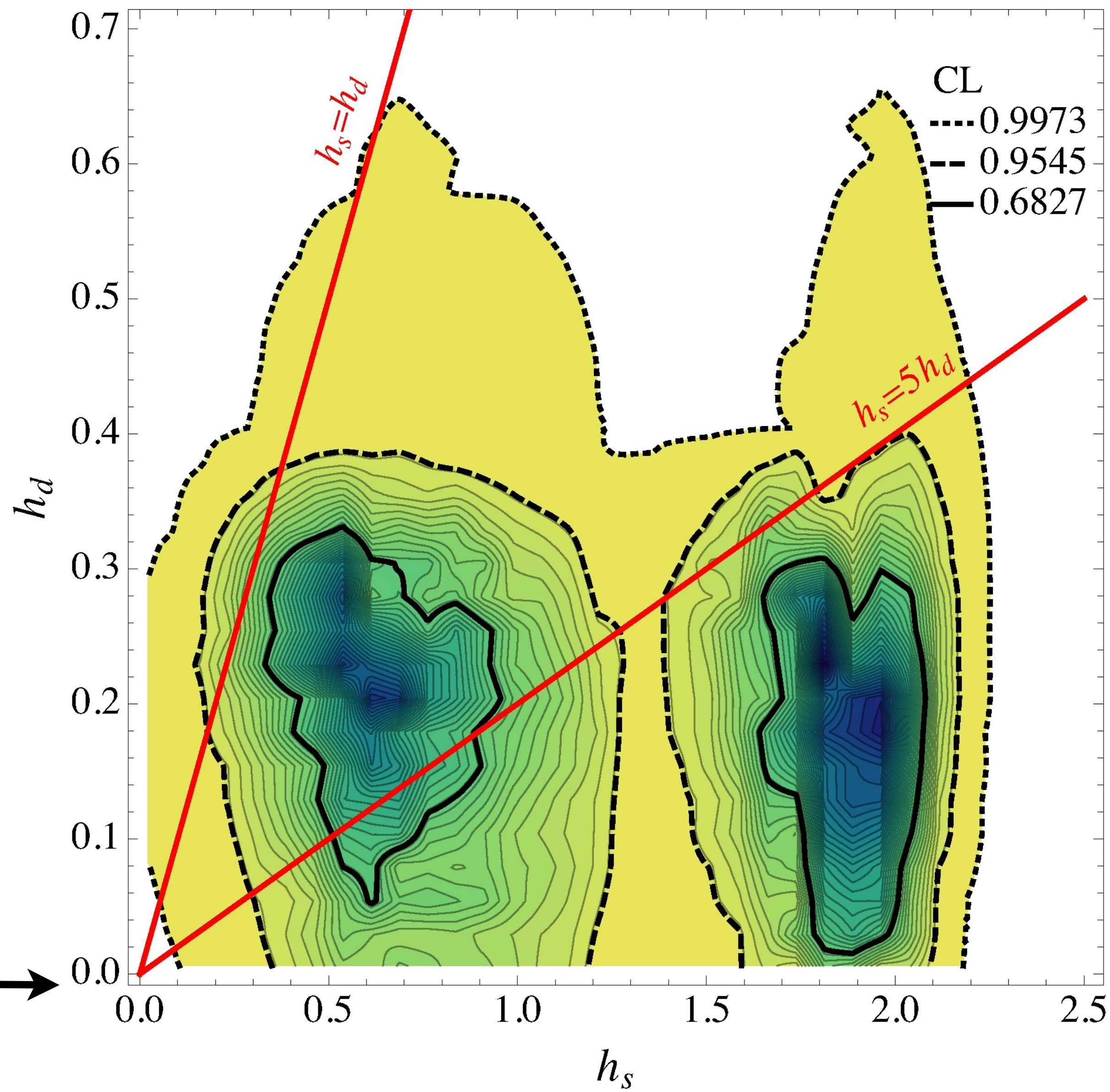
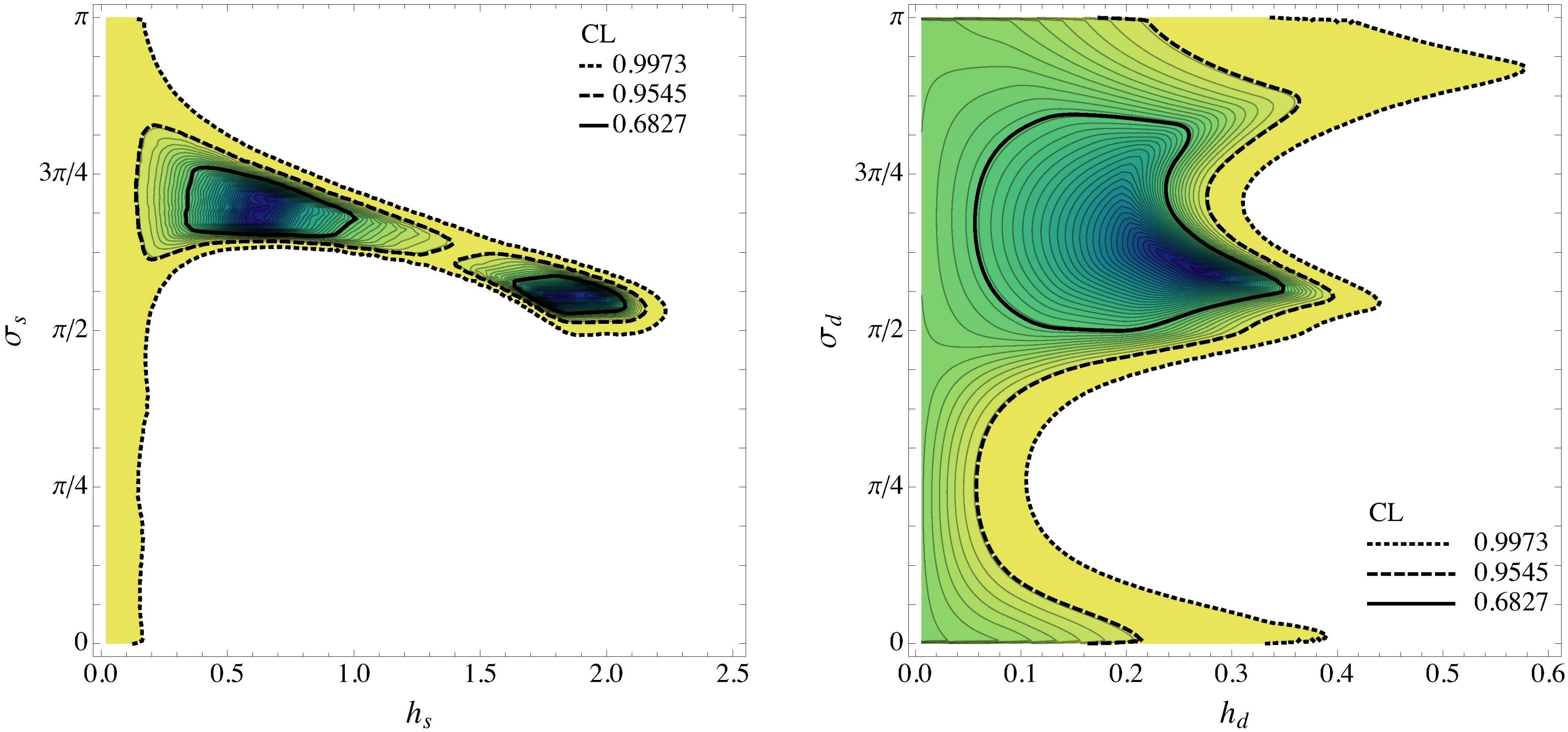


SM →

Data favors $h_s > h_d$

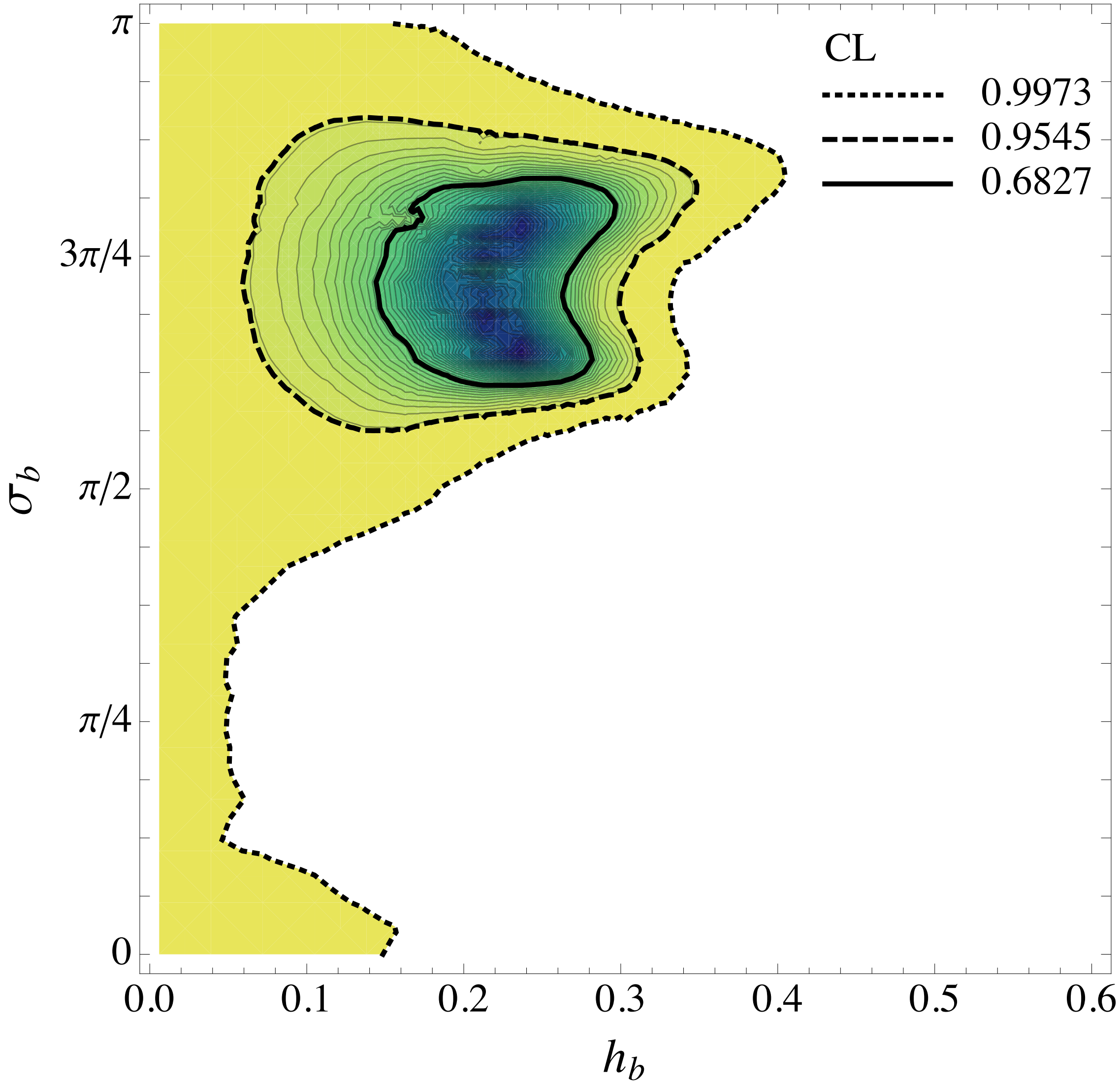
Allowed regions in the B_s & B_d systems.



The allowed ranges of h_s, σ_s (left) and h_d, σ_d (right) from the combined fit to all four NP parameters.

Universal case: $h_d = h_s\,, \quad \sigma_d = \sigma_s$

Viable with some tension.



The allowed h_b, σ_b range assuming $SU(2)$ universality.

Lessons from the data, model indep'

- Tension with SM null prediction.

Lessons from the data, model indep'

♦ Tension with SM null prediction.

♦ $SU(2)_q$ approx' universality, $h_s \sim h_d$, can accommodate data; arise in many models with NP effects via 3rd gen'.

Lessons from the data, model indep'

- Tension with SM null prediction.

- SU(2)$_q$ approx' universality, $h_s \sim h_d$, can accommodate data; arise in many models with NP effects via 3rd gen'.

- However, data favors $h_s \gg h_d$, seems more challenging.

(most theoretical explanation involved tuning of parameters)

Some Model Dependent Implications

GMFV: (i) EFT (ii) Higgs exchange (iii) warped Xtra dim'

GMFV(general minimal flavor violation): simple framework that account for data

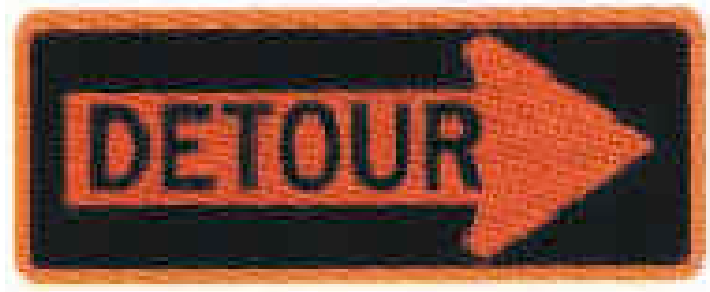
- MFV (@ TeV) + flavor diag' phases => $O(1)$ CPV in b->d,s.

Colangelo, et al. (09); Kagan, et al. (09).

- MFV is a natural limit of many theories & by analyzing the data within MFV we learn about the necessary NP structure that can explain it.

- Surprisingly it can accommodate both above cases:

$$(1)\, h_s \sim h_d\,, \quad (2)\, h_s \gg h_d\,.$$



GMFV: LinearMFV vs NonLMFV & CPV

Kagan, GP, Volansky & Zupan (09);
2 x Gedalia, Mannelli & GP (10).

What defines MFV Pheno'?

- Is CPV is broken only by the Yukawa or flavor diag' phase are present?

- Is the down type flavor group is broken "strongly"?

- Is the up type flavor group is broken "strongly"?

Linear MFV vs. non-linear MFV (NLMFV)

Kagan, GP, Volansky & Zupan (09).

The top Yukawa is large (possibly also bottom one) no justification to treat it perturbatively.

"LO" MFV expansion valid only for $\bar{Q} f(\epsilon_u Y_U, \epsilon_d Y_D) Q$

$\epsilon_{u,d} \ll 1$

Large "logs" or anomalous dim' => $\epsilon_{u,d} = \mathcal{O}(1)$

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We distinguish between 2 cases LMFV & NLMFV:

- *Linear MFV (LMFV)*: $\epsilon_{u,d} \ll 1$ and the dominant flavor breaking effects are captured by the lowest order polynomials of $Y_{u,d}$.
- *Non-linear MFV (NLMFV)*: $\epsilon_{u,d} \sim O(1)$, higher powers of $Y_{u,d}$ are important, and a truncated expansion in $y_{t,b}$ is not possible.

What defines MFV Pheno'?

- If flavor diag' phase are present then one can get large b->d,s CPV with: $(B_s)_{\rm CPV} \geq (B_d)_{\rm CPV}$ or $h_s \geq h_d$

Kagan, GP, Volansky & Zupan (09).

- Only if down type flavor group is broken "strongly" then we can expect $(B_s)_{\rm CPV} > (B_d)_{\rm CPV}$ or $h_s > h_d$

Since new non-universal CPV $\propto [Y_u Y_u^\dagger, Y_d Y_d^\dagger]$

Gedalia, Mannelli & GP (10);
Blum, Hochberg & Nir (10).

MFV, effective operators

Ligeti, Papucci, GP, Zupan.

- **Universal solution:** $(h_s \sim h_d)$

$$\Lambda_{\mathrm{MFV};1,2,3} \gtrsim \{8.8,\ 13\,y_b,\ 6.8\,y_b\}\sqrt{0.2/h_b}\ \mathrm{TeV}\,.$$

$$O_1^{bq} = \bar{b}_L^\alpha \gamma_\mu q_L^\alpha\, \bar{b}_L^\beta \gamma_\mu q_L^\beta,\ O_2^{bq} = \bar{b}_R^\alpha q_L^\alpha\, \bar{b}_R^\beta q_L^\beta,$$

- **Non-univ. solution:** $(h_s \gg h_d)$

$$O_4^{\mathrm{NL}} = \frac{c}{\Lambda^2_{\mathrm{MFV};4}}\left[\bar{Q}_3 (A_d^m A_u^n Y_d)_{3i} d_i\right]\left[\bar{d}_3 (Y_d^\dagger A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i\right].$$

$$\Lambda_{\mathrm{MFV};4} \gtrsim 13.2\,y_b\sqrt{m_s/m_b}\ \mathrm{TeV} = 2.9\,y_b\ \mathrm{TeV}\,.$$

Scalar exchange

Buras, et al. (10); Dobrescu, et al. (10); Jung, et al. (10); Nir et al. (10).

- 2HDM a natural arena to generate flavor & CPV within MFV.
- Universal solution can easily be generated via $\mathcal{O}_2$
- Non-univ. solution only if $\mathcal{O}_4 \gg \mathcal{O}_2$

Vector exchange (KK gluon)

Delaunay, Gedalia, Lee & GP (10)

- Radical solution to little RS CP problem via bulk realization of Rattazzi & Zaffaroni's flavor model.

- New type of GMFV models with large LL and/or RR currents.

- Low KK scale + improve naturalness as a bonos => exciting LHC phenomenology => linkage between high & low pT data!

Summary

♦ Data seem to suggest for new source of CPV.

♦ Consistent NP interpretation favoring large B_s contributions; if no direct CP (width diff' => from data) clean theoretically.

♦ Can be accounted for by MFV (including $B_s > B_d$).

♦ Possible linkage to NP scalar GMFV physics (UV physics fuzzy).

♦ Ultra natural warped models => GMFV => can explain the data via KK gluon exchange, via LLRR operators.

♦ Low KK scale => soon tested @ LHC+flavor gauge bosons.